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Isomeric transitions in Pb^{205}

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With 9 figures in the text

ABSTRACT

From measurements with electromagnetically isotope-separated samples in a double-focusing β-spectrometer, a (26.22 ± 0.01) keV transition in Pb^{205} has been identified from its internal L_{I}, L_{II}, L_{III}, M_{I}, M_{II}, M_{III}, M_{IV}, N_{I}, N_{III} and O_{I} conversion lines. The multipolarity has been proved to be $M2$. There is strong evidence that this transition takes place from a 4.0 msec $i_{13/2}$ state of 1013.8 keV to the 987.6 keV state in Pb^{205}, thus causing the latter state to appear metastable, as has earlier been reported. This suggestion is also supported by the identification of a 310.5 keV $E3$ transition which probably takes place between the isomeric state and the 703.3 keV state. Furthermore, there is reason to believe that the expected $M4$ transition to the ground state is seen as part of a radiation of 1014.0 keV observed in the decay of Bi^{205}. The separation between the $i_{13/2}$ and $f_{5/2}$ levels is found to fit well into the systematics of the odd lead isotopes.

The electromagnetically separated sources were used also for a conclusive establishment of a 262.8 keV $M1$ transition in Pb^{205} (cf. the 262.8 keV $M1$ transition in Pb^{206}). The possibility that this transition is associated with the first excited state is discussed. Some further conversion lines were also studied in the double-focusing spectrometer. In addition, the relative intensities of the *KLL* Auger lines in lead were measured and found to be in fairly good agreement with theoretical, relativistic calculations.

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Introduction

From nuclear shell model theory, isomeric $i_{13/2} \rightarrow f_{5/2}$ transitions are expected to take place in the odd-mass nuclides in the vicinity of the double-magic Pb^{208}. Many such *M*4 transitions have also been found experimentally. In a study of nuclear isomerism in the odd-mass lead isotopes, Stockendal *et al.* [1] showed that the energies and gamma-transition probabilities of the *M*4 transitions in Pb^{197}, Pb^{199}, Pb^{201}, Pb^{203} and Pb^{207} vary in a systematic way as functions of the neutron number. From the very smooth curves representing these functions one could predict that an *M*4 transition in Pb^{205} would take place with an energy of 980 ± 40 keV and a half-life of (1.5 ± 0.5) sec. Experiments were performed with the purpose of detecting such a transition. A Bi^{205} activity (unavoidably mixed with small amounts of Bi^{206} and Bi^{207}) was absorbed in an ion exchange column, and any lead activity produced in the decay of the bismuth could be rapidly milked out of the column and transferred to a detector. However, no activity was observed, apart from 0.8 sec Pb^{207m} [1, 2].

An extensive investigation of the decay of Bi^{205} was at the same time in progress at this institute (Schmorak *et al.* [3]). The preliminary results then available showed that, of the transitions following the decay of Bi^{205}, four had energies within or near the energy region of interest, namely those of about 988, 1003, 1014 and 1044 keV. From the result of the milking experiments, however, it was fairly certain that, for intensity reasons, none of these transitions could be associated with a 1.5 sec isomer in Pb^{205}.

Another type of experiment was performed by Bendel *et al.* [4], who studied (γ, n) reactions in natural lead. Also in this investigation no isomer Pb^{205m} was seen.

One of the most plausible explanations of the failure to observe an isomer in Pb^{205} seemed to be the possibility that a complex state of intermediate spin is situated between the $i_{13/2}$ and $f_{5/2}$ levels, thus making an observation of *M*4 radiation from the $i_{13/2}$ level impossible [1]. The final results of the above-mentioned investigation of Schmorak *et al.* [3] showed that this certainly also is the case. Their level scheme of Pb^{205} includes a $9/2-$ (or $7/2-$) level at 703.3 keV and a $7/2-$ (or $9/2-$) level at 987.6 keV.

The problem of "the missing isomer in Pb^{205}" thus seemed to be satisfactorily solved, until recently an activity assigned to Pb^{205} having 4.8 msec half-life was observed by Vegors and Heath [5] in the electron-capture decay of Bi^{205}. The isomeric level was found to decay with the emission of 987.8, 703.3 and 284.4 keV gamma rays with relative transition intensities of 100, 10 and 10, respectively, but no other gamma rays of energy greater than 10 keV were observed in the decay of this isomer. It is very probable that the delayed 987.8 keV gamma ray is identical with the gamma ray of 0.9 MeV and (6.5 ± 0.5) msec half-life which had been observed earlier by Leipunskii *et al.* [6] when Tl was bombarded with 20 MeV protons.

The question now arose as to whether the 987.8 keV transition, after all, is identical with the $i_{13/2} \rightarrow f_{5/2}$ transition searched for. This suggestion must, however, be rejected for the following reasons. Firstly, the half-life observed is of the order of 300 times shorter than predicted from the systematics, and since $M4$ transitions are found to be very regular in their behaviour generally (see e.g. ref. [1]), this would mean a serious descrepancy. Secondly, an $M4$ assignment of the 987.8 keV transition would be in conflict with the fact that the results of Schmorak *et al.* [3] indicate $E2$ (or possibly $E1$) character for this transition. Furthermore, it could recently be definitely concluded from an absolute measurement by Stockendal and Hultberg [7] of the K-conversion coefficient of the 987.8 keV transition that the multipolarity is mainly $E2$ (cf. experimental value: 0.0049 ± 0.0009; theoretical values [8]: 0.0054 ($E2$) and 0.12 ($M4$)).

There now seemed to be two possibilities to explain the results of Vegors and Heath (cf. ref. [5]):

1. The 988 keV level itself is isomeric with the main de-excitation taking place to the ground state with an extremely slow $E2$ transition. This possibility seems not very likely, especially since it would mean that also the competing 284.2 keV $M1$ transition taking place from the 988 keV level would be considerably delayed.

2. The 988 keV level itself may not be isomeric but may be fed entirely by a highly converted, low-energy transition from an isomeric level. There was in the results of Vegors and Heath some evidence (although not conclusive) that this may be the case. The measurements indicated that the 987.8 keV transition was in coincidence with L X-rays, whereas no coincidences were found with K X-rays. This would therefore imply that the isomeric level is very close to the 988 keV level, lying between about 16 and 88 keV above this level [5].

The present investigation was undertaken in order to clarify whether such a low-energy transition feeding the 988 keV level really exists. As will be shown below, this obviously is the case.

I. Experiments and results

1. *Source preparation*

The first bismuth source used in the experiments was produced by bombarding natural lead for 6 hours with about 45 MeV protons in the synchrocyclotron of the Gustaf Werner Institute in Uppsala. In order to improve the results of measurements, a stronger source was necessary, and therefore later another irradiation of about 500 μAh was made in the 225 cm cyclotron of the Nobel Institute. This time a target of radiogenic lead (88 % Pb^{206}, 9 % Pb^{207} and 3 % Pb^{208}) was bombarded with 22 MeV deuterons for about 20 hours. The bismuth activity scraped off the target was in this case found to give a dose rate of 1 R/h at a distance of 30 cm one month after the bombardment.

In each case the bismuth activity was chemically separated from the target material according to the procedures described elsewhere [1]. In order to get as thin a beta-spectrometer sample as possible and also in order to get the Bi^{205} separated from other bismuth activities present (mainly Bi^{206}), the source was electromagnetically sepa-

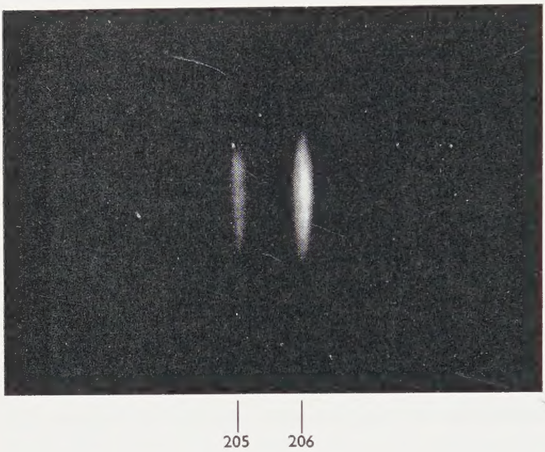

Fig. 1. Autoradiogram of the electromagnetically isotope-separated activities of Bi^{205} and Bi^{206} collected onto a thin aluminium foil. The picture is shown in natural scale. The rectangular sources, which could be cut out of this foil, were used for the measurements in the double-focusing β-spectrometer. The Bi^{205} source gave a dose rate of about 25 mr/h at a distance of 10 cm.

rated (cf. [9] and [10]). The activities were collected onto a thin aluminium foil (about 1.9 mg/cm^2). Fig. 1 shows in natural scale an autoradiogram of the foil with the separated activities from the second bombardment. It is quite obvious that the sources, which could be cut out as narrow strips from the foil, had dimensions which made them very convenient for measurements in a double-focusing beta spectrometer. Furthermore, it was found that less than 1 % of the Bi^{205} activity was mixed into the Bi^{206} source, and less than 3 % of the Bi^{206} activity was mixed into the Bi^{205} source. Obviously the advantages of the electromagnetic separation were achieved at the cost of source strength, since the efficiency did not exceed 3 % in either of the separations.

2. *Beta-spectrometer measurements*

The measurements were carried out in a double-focusing beta spectrometer [11]. To make the detection of very low energy electrons possible it was necessary to use a very thin window for the G.M. tube. A 20 μg/cm^2 formvar foil was therefore made and supported on a brass grid of 0.5 mm thickness and with a transmission of about 90 %. The cut-off energy of this window was measured to be (2.3 ± 0.2) keV. This means that no intensity correction due to absorption in the window [12] had to be applied to any of the internal conversion lines studied. It was also checked in a special measurement that no correction had to be made for any of the lines measured due to a possible penetration of electrons through the meshes of the grid.

a. *The 26.22 keV M2 transition*

Five different measurements of the low-energy spectrum were carried out using the electromagnetically separated sources of Bi^{205}. The upper part of Fig. 2 shows one of these runs made with the spectrometer adjusted to a relative half-width of about 0.35 %. By the aid of the data of L Auger transitions in Tl and Bi given by Sujkowski and Slätis [13] it was possible to decide which lines in the spectrum are not due to Auger electrons. A direct discrimination was, however, also made by measuring the same region with the electromagnetically separated source of Bi^{206}. The latter spectrum is shown in the lower part of Fig. 2. The scale on the vertical axis has been chosen

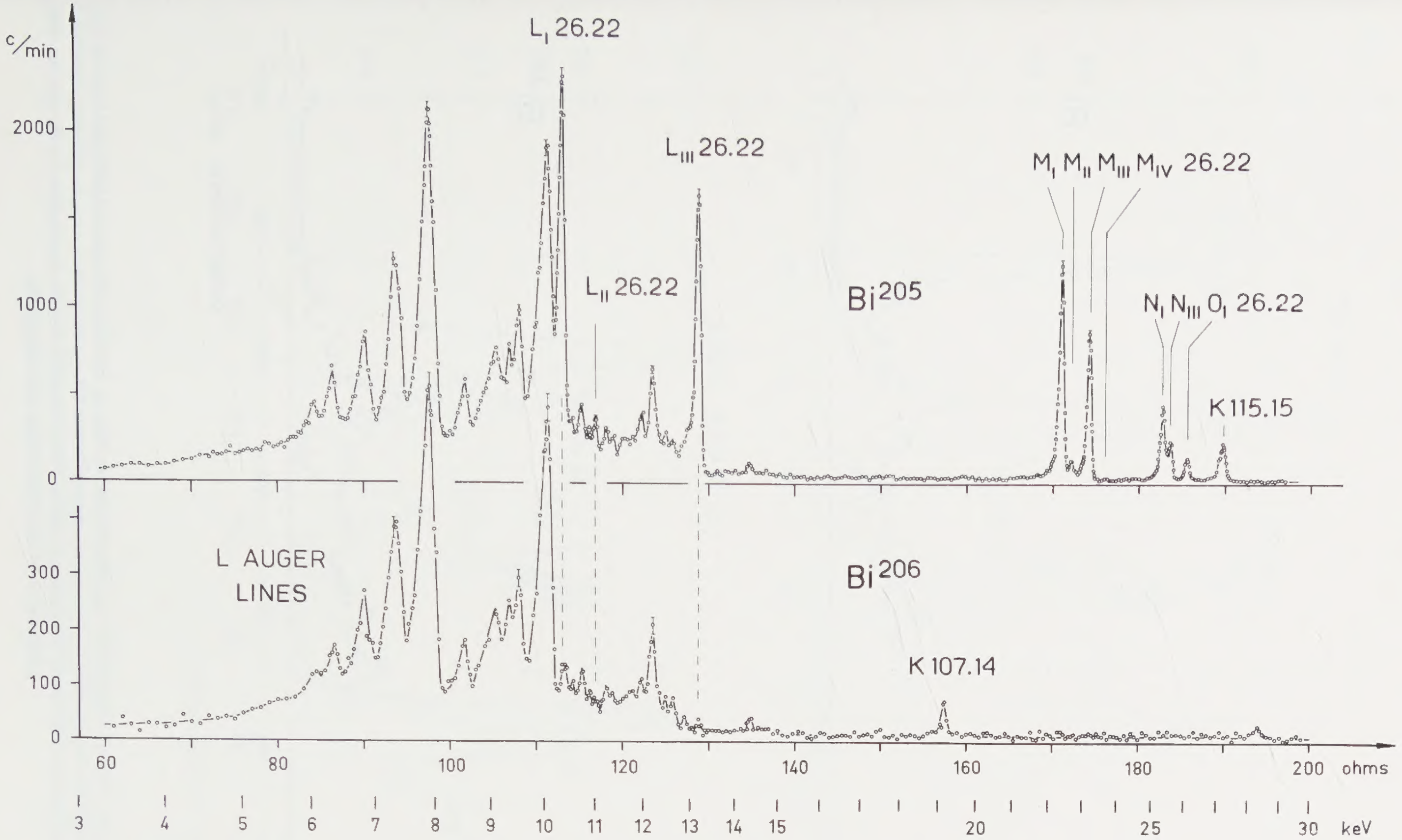

Fig. 2. Identification of the internal conversion lines of the 26.22 keV *M*2 transition in Pb^{205} from a comparison between Bi^{205} and Bi^{206} spectra, as measured in a double-focusing spectrometer. Electromagnetically isotope-separated sources were used (cf. Fig. 1), and the spectrometer was adjusted to a relative half-width of about 0.35 %. The cut-off energy of the G.M. window was about 2.3 keV. Details of the spectra are shown in Figs. 3 and 4.

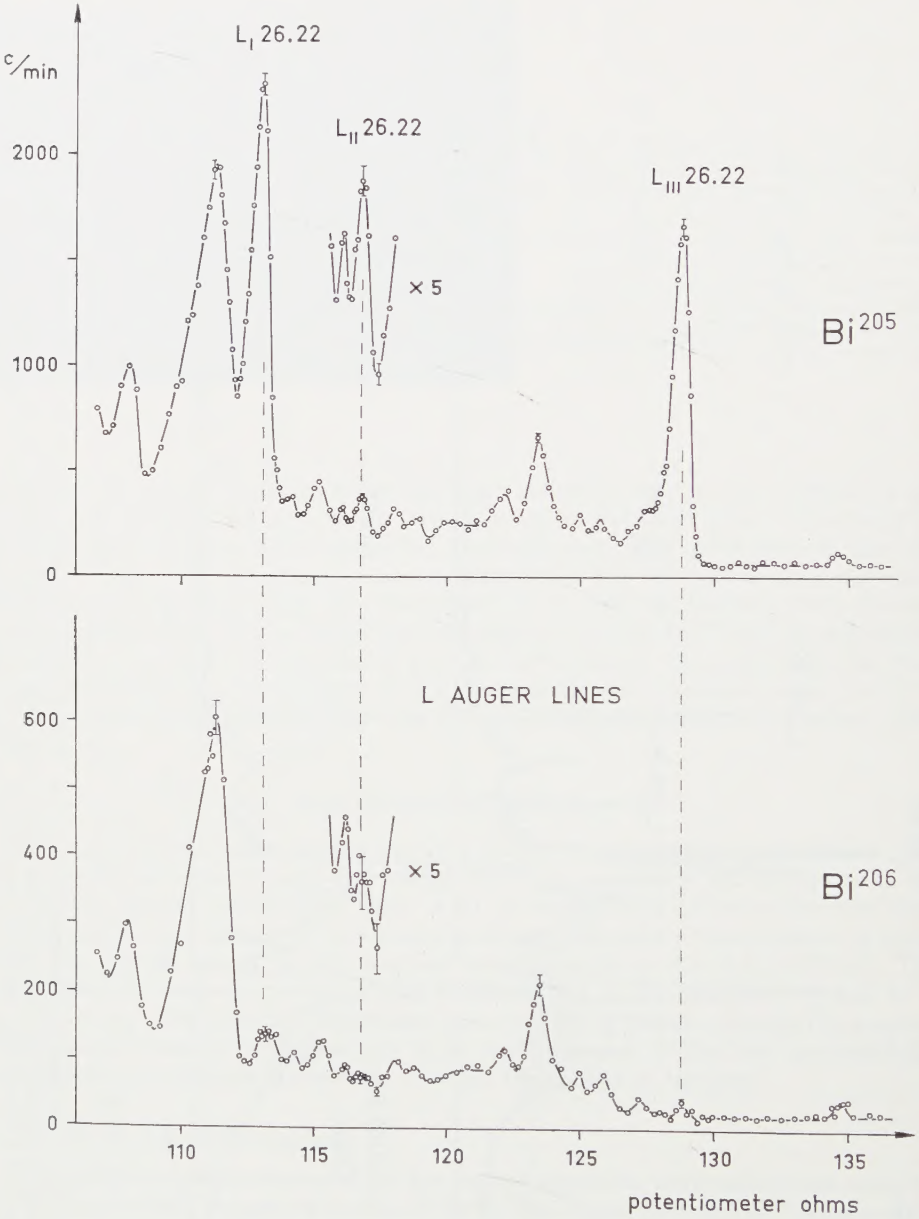

Fig. 3. Parts of the Bi^{205} and Bi^{206} spectra shown in Fig. 2. Besides the strong internal L_I and L_{III} conversion lines of the 26.22 keV transition, also the weak L_{II} component can be clearly identified from the comparison between the two spectra. The relative L-line intensities indicate an $M2$ assignment of the transition (cf. Table 2).

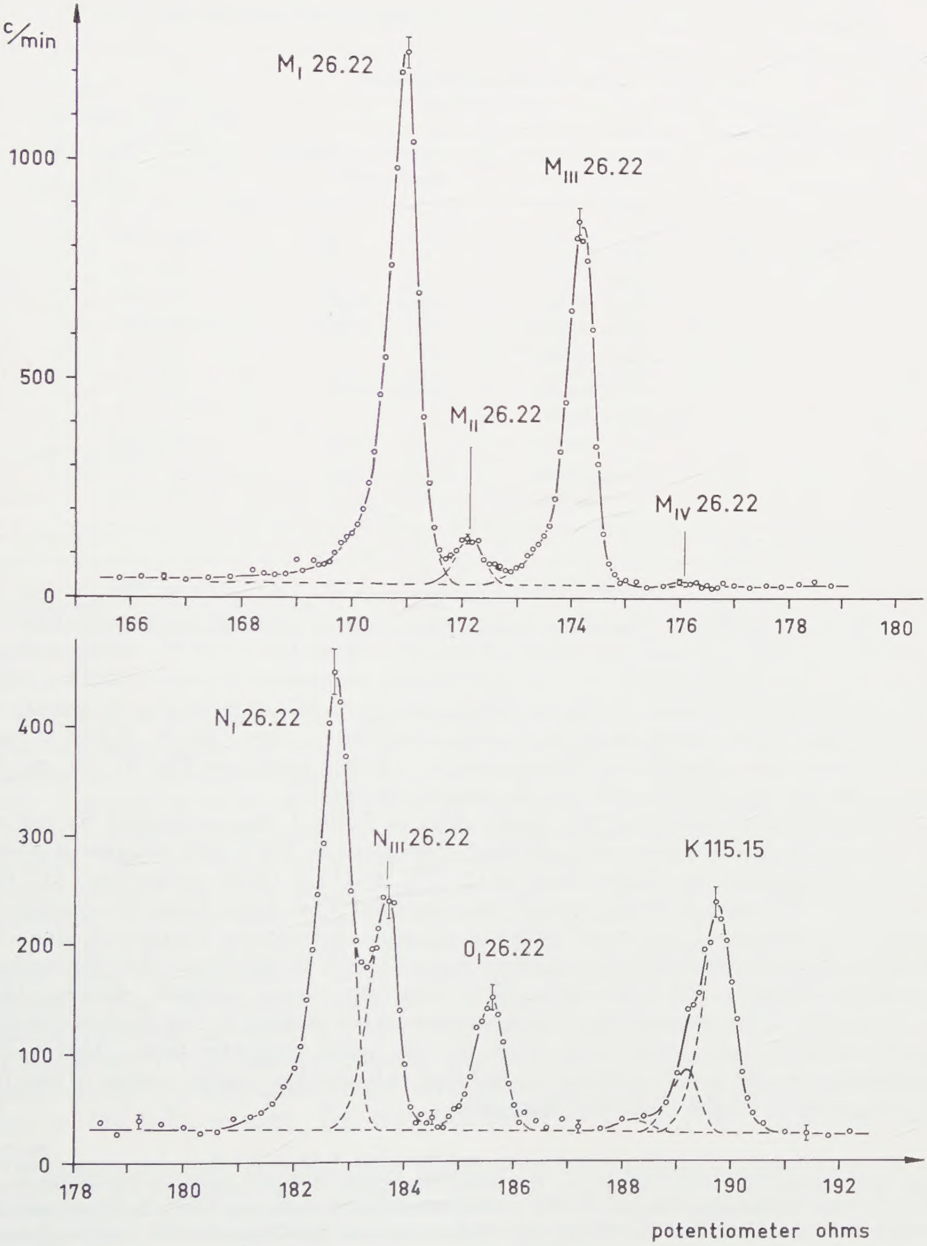

Fig. 4. The *M, N* and *O* conversion-line groups of the 26.22 keV transition in Pb^{205} as measured in a double-focusing spectrometer using an electromagnetically separated source of Bi^{205} (cf. upper part of Fig. 2). Resolution: about 0.35 %. The relative intensities of the *M* lines support the *M*2 assignment of the transition (cf. Table 2).

Table 1. Internal conversion lines of the 26.22 keV transition in Pb^{205}.

Adopted transition energy (keV)	Internal conversion lines measured in		Relative conversion-line intensity ($I_{K\,703.3} = 100$)
	double-focusing spectrometer	permanent magnet spectrometer	
26.22 ± 0.01	L_I 26.22	—	1490 ± 90
	L_{II} 26.21	—	45 ± 20
	L_{III} 26.22	L_{III} 26.21	920 ± 60
	M_I 26.223	M_I 26.24	520 ± 30
	M_{II} 26.217	—	36 ± 4
	M_{III} 26.225	M_{III} 26.24	300 ± 20
	M_{IV} 26.22	—	5 ± 3
	N_I 26.223	N_I 26.20	160 ± 10
	N_{III} 26.217	N_{III} 26.21	75 ± 10
	O_I 26.222	O_I 26.21	44 ± 5

so as to make possible a direct comparison between the two spectra. Thus it can be definitely concluded from Fig. 2 that there exist some low-energy conversion lines in the Bi^{205} spectrum. From the measured energies these lines can be interpreted as the L_I, L_{II}, L_{III}, M_I, M_{II}, M_{III}, M_{IV}, N_I, N_{III} and O_I conversion lines of a (26.22 ± 0.01) keV transition[1] (cf. Table 1). Part of Fig. 2 is drawn enlarged in Fig. 3, mainly in order to show more convincingly the existence of the L_{II} line. The M, N and O lines of the 26.22 keV transition are also shown in a larger scale (see Fig. 4). (It can be remarked that the evidence for the M_{IV} line is very poor.)

The calibration underlying the energy data of Table 1 was performed by use of, (1) the measured conversion lines of other transitions in Pb^{205}, the energies of which should be accurate to better than $5:10^4$ [3]: K 115.2 (more accurately: 115.15), K 260.5, L_I 260.5 and K 703.3, and, (2) the measured KLL Auger lines, the energies of which were calculated using the values of effective incremental charge ΔZ given by Mladjenović and Slätis for Auger transitions in Bi [15]. It was found that the mutual agreement between all these calibration data was almost perfect, showing that the linearity of the momentum versus potentiometer reading in the double-focusing spectrometer is quite good, even down to very weak magnetic fields. This is also emphasized by the good consistency obtained between the energy values of the ten conversion lines of the 26.22 keV transition.

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[1] It was found that the relative half-width was the same, 0.35 %, for these low-energy conversion lines (except for the L lines) as for conversion lines of higher energies, e.g. K 260.5 and K 703.3. The broadening observed for the L lines (about 0.6 % resolution for L_I 26.22) is probably mainly due to the fact that the active atoms had penetrated the aluminium foil to a small depth in the electromagnetic separation (cf. [14]).

It may also be seen in Fig. 2 that the Bi^{206} lines of the very lowest energy are somewhat flattened out as compared with the corresponding Bi^{205} lines. This might also be an effect of source thickness, since the Bi^{206} source should have contained a small amount of inactive Pb^{206} introduced by the $PbCl_2$ carrier used in the electromagnetic separation (cf. the abundances of natural Pb: 52.3 % Pb^{208}, 22.6 % Pb^{207}, *23.6 %* Pb^{206} and 1.5 % Pb^{204}; it should be noted that there is *no* stable Pb^{205} isotope).

Table 2. Deduction of multipolarity for the 26.22 keV transition.

Multi-polarity	Relative internal conversion intensities							
	L_{I}	L_{II}	L_{III}	M_{I}	M_{II}	M_{III}	M_{IV}	M_{V}
Theoretical[a]								
$E1$	560	730	1000	720	680	1000	310	380
$E2$	22	1000	1000	21	840	1000	20	16
$E3$	12	880	1000	15	940	1000	150	260
$E4$	7	760	1000	11	1030	1000	1700	2000
$E5$	4	680	1000	8	1200	1000	7000	7700
$M1$	100000	10800	1000	110000	12000	1000	170	94
$M2$	*1800*	*90*	*1000*	*1600*[b]	*106*	*1000*	*22*	*1*
$M3$	120	5	1000	180	10	1000	17	34
$M4$	27	1	1000	56	3	1000	17	300
$M5$	10	0	1000	26	1	1000	19	910
Experimental								
$M2$[c]	*1620*	*~50*	*1000*	*1730*	*120*	*1000*	*~17*	*<10*

[a] Obtained from the L-conversion coefficients of Sliv and Band [8] and from the M-conversion coefficients given by Rose [18]. The L_{III} and M_{III} intensities have been normalized to 1000.

[b] The calculated values [18] for $Z = 80$ and 85, M_{I} shell, multipolarity $M2$, $k = 0.05$, seem to be unreliable and have therefore not been used in the deduction of this intensity value.

[c] The $M2$ assignment seems reasonable also from a consideration of the partial γ-half-life (see Section II.2).

It should be mentioned that some of the conversion lines of the 26.22 keV transition had been observed earlier (although unassigned) [3] on a photographic film exposed in a permanent magnet beta spectrometer [16] at this institute. These lines were, however, recorded as very weak due to the low sensitivity of the photographic film for low-energy electrons. As a matter of fact, the most intense conversion line, L_{I} 26.22, was not seen at all in the film. The energy values, as obtained from a re-examination of the film, are included in Table 1 and show, as can be seen, good agreement with the result from the double-focusing beta spectrometer.

In Table 1 are also given the relative conversion-line intensities (deduced from the areas under the conversion lines), which are the weighted mean values from the different runs. The half-life value of 15.0 days was used in the decay corrections. Intensity corrections (about 4 % for L_{I} 26.22) were made in accordance with the results of Bergkvist [17] on relative intensity measurements with the double-focusing beta spectrometer.[1] As mentioned above, no corrections had to be applied due to absorption in the G.M. window. The uncertainties given in the table are the statistical errors.

A comparison with the intensities tabulated for the conversion lines earlier found in the decay of Bi^{205} [3], shows that the lines of the 26.22 keV transition are relatively strong. Thus it is found, for instance, that the L_{I} 26.22 line is more than 8 times more intense than the strongest line previously known.

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[1] The quoted investigation does not consider lines with lower electron energy than 24 keV. The correction factors applied to the lines of the 26.22 keV transition were therefore found by extrapolation of the data. A possible systematic error, which may be introduced here, is, however, considered to be not larger than a few percent (Bergkvist, private communication).

Table 3. Internal conversion lines of the 310.5 keV transition in Pb^{205}.

Adopted transition energy (keV)	Internal conversion lines measured in		Relative conversion-line intensity ($I_{K\,703.3} = 100$)
	double-focusing spectrometer with Bi^{205} source	permanent magnet spectrometer with $Bi^{205} + Bi^{206}$ source	
310.5 ± 0.1	K 310.5[a]	K 310.5	4.3 ± 1.0
	L_{II} 310.3[b]	L_{II} 310.4[b]	6.1 ± 0.6
	L_{III} 310.6	—[c]	1.6 ± 0.4
	M_{II} 310.6	M_{II} 310.7	2.3 ± 0.6
	N_{II} 310.6	—[d]	< 1.7

[a] Not well resolved from neighbouring Bi^{205} lines.

[b] L_I line interferes.

[c] L_{III} line hidden by K 386.0 and L_I 313.6 in Bi^{206} decay.

[d] N_{II} line masked by K 398.1 of Bi^{206}.

The relative intensity values found for the L- and M-conversion lines can be used for the assignment of multipolarity to the new transition. In Table 2 the experimental values are given together with the theoretical values for different multipolarities (L_{III}- and M_{III}-conversion intensities normalized to 1000). The theoretical values were deduced for the energy 26.22 keV from the L-conversion coefficients given by Sliv and Band [8] and from the M-conversion coefficients given by Rose [18]. From an inspection of Table 2 it must be concluded that no other multipolarity assignment than $M2$ can come into consideration for the 26.22 keV transition. Furthermore, the very good agreement between the theoretical values for $M2$ for both L- and M-subshells, indicates that the transition has a very pure $M2$ character. The assignment is supported also from a consideration of half-life (see Section II.2).

There seems to be no doubt that the 26.22 keV $M2$ transition (having $I_\gamma \sim 5.5 \times \times 10^{-5} \times I_{\gamma\,987.8}$) is identical with the highly converted, low-energy transition expected to take place from an isomeric level of 4.8 msec half-life. The energy of this level would then be 987.6 keV (level energy [3]) + 26.2 keV = 1013.8 keV. Since the 987.6 keV level probably is a $9/2-$ level, the $M2$ assignment of the 26.22 keV transition would suggest spin and parity $13/2+$ for the isomeric state. It may be pointed out here that, according to theoretical predictions of Pryce [19] and True [20], a $13/2+$ level is expected at about 1100 and 1050 keV, respectively.

b. *The 310.5 keV E3 transition*

The inclusion of a $13/2+$ state at 1013.8 keV in the level scheme of Pb^{205} would now suggest the search for a transition of about 310.5 keV taking place between this level and the 703.3 keV level. Since the latter state has been assigned $9/2-$ (or $7/2-$), the multipolarity of such a transition would be $M2$ or $E3$. A re-examination of earlier data was therefore made. In a photographic film, exposed with a $Bi^{205} + Bi^{206}$ source in a permanent magnet beta spectrometer, some weak lines were found which can be interpreted as (1) K 310.5, (2) L_I 311.1 or L_{II} 310.4 and (3) M_I 311.0 or M_{II} 310.7

Table 4. Deduction of multipolarity for the 310.5 keV transition.

Multipolarity	Internal conversion ratios		Relative internal conversion intensities		
	$K/(L_I+L_{II})$	$(L_I+L_{II})/L_{III}$	L_I	L_{II}	L_{III}
Theoretical[a]					
$E1$	6.5	8.0	530	100	78
$E2$	2.3	3.1	49	100	48
$E3$	*0.69*	*3.4*	*20*	*100*	*36*
$E4$	0.31	3.6	13	100	31
$E5$	0.13	4.0	11	100	28
$M1$	5.7	147	960	100	7
$M2$	4.2	16	680	100	49
$M3$	3.0	3.6	48	100	160
$M4$	2.0	1.7	37	100	270
$M5$	1.4	1.0	29	100	400
Experimental					
$E3$[b]	*0.7* ± 0.2	*3.8* ± 1.0	*< 30*	*100*	*~ 30*

[a] Deduced from the internal conversion coefficients given by Sliv and Band [8].
[b] The assignment is supported by the partial γ-half-life (see Section II.2).

(cf. Table 3). (A possible L_{III} line would be unresolved from the Bi^{206} lines K 386.0 and L_I 313.6, while N lines would be masked by the strong K 398.1 of Bi^{206}.) A comparison with a later exposure shows that the three lines observed decay with the Bi^{205} half-life.

The *first* conversion line, K 310.5, had previously been assigned L_{III} 235.9 [3], but, from a comparison between experimental and theoretical L-subshell ratios, it must be concluded that this line—or at least the main part of it—belongs to another transition. The *second* line, which appears to have about the same intensity as the first one, was earlier assumed to be the K line of a 383.2 keV transition, other conversion lines of which were not detected. The *third* and weakest line was previously not assigned.

Thus there is actually evidence for a transition in Pb^{205} having the expected energy. As indicated above, the $K/(L_I+L_{II})$ ratio is visually estimated to be about 1, and this would suggest multipolarity $E3$ for the transition (see below). This assignment would also explain the observed fact that conversion takes place in the L_{II} and M_{II} subshells, rather than in the L_I and M_I subshells.

A further study of the new transition was made in the double-focusing spectrometer with an electromagnetically isotope-separated sample of Bi^{205}. Because of their low intensities, the conversion lines had to be measured at a relatively low resolution, 0.69 %. Hence the K line could not be satisfactorily resolved from neighbouring lines. It appeared that a previously unknown Bi^{205} line, with the probable assignment K 313.1, is situated close to K 310.5 and is somewhat stronger than this line (see Appendix 1.e). (In earlier measurements K 313.1 had been hidden by K 313.6 of Bi^{206}.) Furthermore, the L_I line of this new transition very nearly coincides with the L_{III} line of the 310.5 keV transition. The M_{II} line of the 310.5 keV transition was found also in this run and, in addition, the N_{II} line, which earlier had been completely masked by the strong K 398.1 line of Bi^{206}.

The energy- and intensity values obtained from the measurements in the double-focusing spectrometer are given in Table 3 together with the data from the permanent magnet spectrometer. Because of the experimental difficulties mentioned above, part of the information is somewhat indefinite. As also pointed out above, the data from the photographic film favour an $E3$ assignment for the 310.5 keV transition. The same multipolarity is suggested also from the results obtained with the double-focusing spectrometer. This is clear from Table 4, where the experimental internal conversion ratios are compared with the theoretical ones [8]. It should be mentioned that an $E3$ assignment seems reasonable also from a consideration of half-life (see Section II.2).

c. *The 1014.0 keV M4 transition*

It is interesting to find that the energy of the proposed 13/2 + state coincides within the experimental error with the energy of a transition previously known in the decay of Bi^{205}, and it is therefore tempting to believe that the observed transition is identical with the $M4$ transition searched for in Pb^{205}. The transition energy has been found to be 1014.0 keV [2] or 1014.2 keV [3]. A remeasurement of the K-conversion line was made with an electromagnetically separated source of Bi^{205} in the double-focusing spectrometer. The value obtained is 1013.9 keV. The three results lead to an adopted energy value of 1014.0 keV for the transition.

It should also be mentioned that in the decay scheme of Bi^{205} given by Schmorak *et al.* [3], a level is tentatively placed at 1552.3 or 1014.2 keV. Since the energies of the 1552 and 1014 keV gamma rays add up to the energy of a level in Pb^{205}, the two gamma rays were suggested to be emitted in cascade, but the order of emission was not known. The present results, however, might indicate that the 1552 keV transition populates the isomeric state (see, however, Section II.2).

For the purpose of multipolarity determination,[1] it would have been convenient to measure also the L-conversion line of the 1014.0 keV transition with the electromagnetically separated sample, but the source was considered too weak for such a measurement to be profitable. However, the K and L lines have both been measured with a stronger, unseparated source in the double-focusing spectrometer. The resolution was 0.35 %, but nevertheless the lines are not completely resolved from the conversion lines of the 1018.8 keV transition in the decay of Bi^{206}. The result obtained from this run is that

$$K/(L_{\mathrm{I}}+L_{\mathrm{II}}) = 4.6 \pm 0.8.$$

The theoretical values [8] which might be considered for a comparison are: 5.7 ($M1$), 5.2 ($M2$), 4.6 ($M3$), 4.0 ($M4$), 5.2 ($E2$) and 3.7 ($E3$). (For other multipolarities the deviations from the experimental value are larger.) Thus it is seen that the $M4$ assignment may be possible on this basis, but obviously no definite conclusion can be drawn. Actually, there is some evidence (see Section II.2 below), that there exist two transitions in Pb^{205} having almost exactly the same energy, one of which is the isomeric $M4$ transition.

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[1] An attempt has been made to determine the K-conversion coefficient by the method of external conversion [7]. However, because of the weakness of the photoline only a lower limit was obtained, excluding multipolarity $E1$.

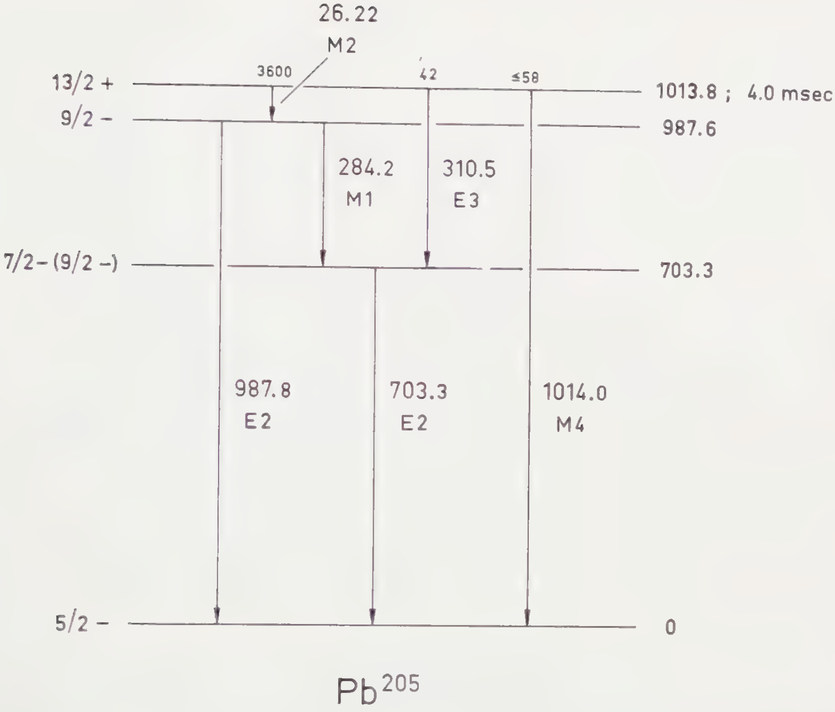

Fig. 5. Decay of the 4 msec $i_{13/2}$ state in Pb^{205}. The total transition intensities indicated at the head of the isomeric transitions, are given in the intensity scale used in Tables 1, 3 and 5 ($I_{K703.3} = 100$). The uncertain intensity value for the $M4$ transition is due to the possible existence of two transitions in Pb^{205} having about the same energy, 1014 keV, as discussed in the text. For clarity the separation between the 1013.8 and 987.6 keV levels is exaggerated.

II. Discussion

1. *Decay of the $i_{13/2}$ state*

Fig. 5 shows the proposed decay scheme of the 13/2 + state in Pb^{205}. The half-life indicated is the most accurate value available ((4.0 ± 0.2) msec), recently measured by Bergström *et al.* [21], using the oscilloscope method. At the head of the isomeric transitions the total transition intensities are given in the units defined by $I_{K\,703.3} = 100$. For the intensity of the $M4$ transition only an upper limit is given due to the possible existence of two transitions having the same energy (see below). The intensities have been calculated from the conversion-line intensities by the aid of the theoretical conversion coefficients [8] for the multipolarities proposed. The conversion-line intensities used for the 26.22 and 310.5 keV transitions are those given in Tables 1 and 3, respectively. In the case of the 1014.0 keV transition, the value of $I_{K\,1014.0} = 5.7$ was used, as obtained from the above-mentioned measurement with the electromagnetically separated Bi^{205} source. From the calculated transition intensities it appears that more than 97 % of the depopulation of the isomeric state takes place via the 26.22 keV transition.

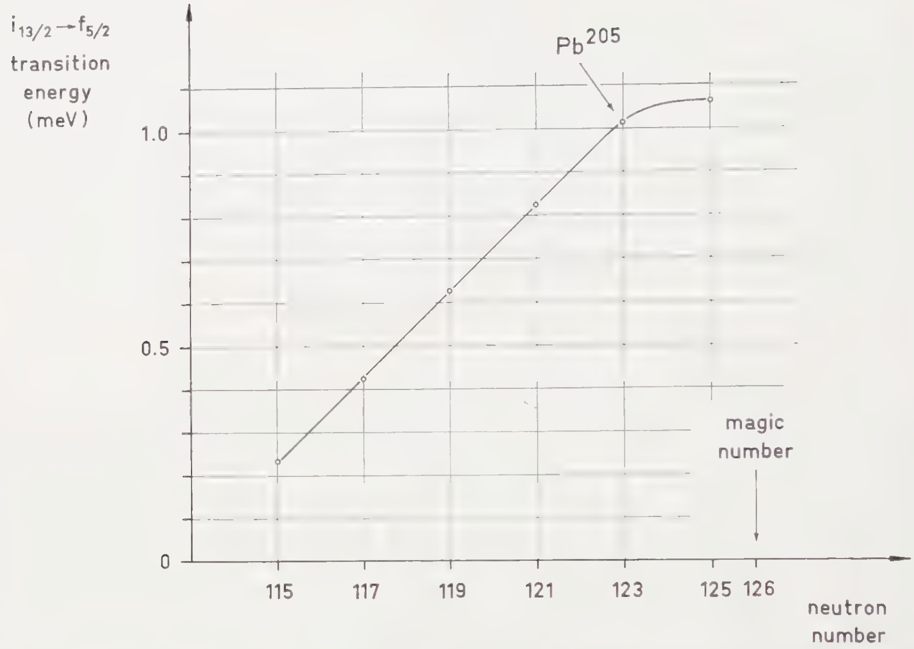

Fig. 6. The energy separation between the $i_{13/2}$ and $f_{5/2}$ levels in the odd Pb isotopes, plotted as a function of the neutron number.

Total transition intensities were also calculated for the 987.8 and 284.2 keV transitions using the K-line intensities given in ref. [3]. (A check of $I_{K\,987.8}$ with the electromagnetically separated sample gave a value in good agreement with the one of ref. [3].) The intensity values thus obtained are 5100 and 590 units, respectively. Hence one finds that only about 65 % of the feeding to the 987.6 keV level takes place via the 26.22 keV transition. This is somewhat surprising since the 987.8 keV gamma ray has been found not to be in coincidence with either K X-rays or any other major gamma rays [5].

The energy separation found between the $i_{13/2}$ and $f_{5/2}$ levels in Pb^{205} can now be compared with the corresponding energy differences which are known for other odd lead isotopes. In Fig. 6 these transition energies are plotted as a function of the neutron number and, as can be seen, the points lie very accurately on a straight line except for the point next to the magic number.

2. *Gamma-transition probabilities*

It is of interest to compare the gamma-transition probabilities found experimentally with those obtained from the theory of Weisskopf for transitions of a single proton [22]. The experimental values are (in sec^{-1}) 1.3×10^{-2} for $\gamma(26.22, M2)$, 1.3 for $\gamma(310.5, E3)$ and 2.4 for $\gamma(1014.0, M4)$ (assuming that the observed 1014.0 keV transition is single). Setting the statistical factor $S = 1$ and using the value $r = 1.20 \times 10^{-13}\ A^{1/3}$ for the nuclear radius, the theoretical values are found to be approximately 35, 420 and 2.3 $\sec^{-1}$, respectively. Thus it appears that the 26.22 keV $M2$ gamma transition is of the order of 2500 times slower than calculated for a single proton transition, while the 310.5 keV $E3$ transition is slower by a factor of about 300. Experience has shown, however, that $M2$ transitions (data known only for three cases) and $E3$ transitions are generally hindered and that deviation factors of these orders of magnitude are not unique [23, 24]. The assignments indicated from the conversion data for the two transitions are thus quite reasonable from a consideration of lifetime, and, furthermore, any other multipole order would be in disagreement with the systematics.

The very good agreement between the experimental and theoretical values given above for the 1014.0 keV transition might at first sight be taken as a support for an $M4$ assignment. According to the systematics [23, 24], however, one would also in this case have expected a deviation factor, and it is a general experience that for $M4$ transitions these factors are remarkably constant. Thus it is found, for instance, that, in the case of the $i_{13/2} \rightarrow f_{5/2}$ transitions in Pb^{199}, Pb^{201}, Pb^{203} and Pb^{207}, the ratios between experimental and theoretical gamma-transition probabilities are 0.22, 0.20, 0.23 and 0.21, respectively. This means for the Pb^{205} case, where the corresponding factor is 1.0, a deviation from the systematics by a factor of 4.5, i.e. a partial half-life of about 0.3 sec instead of about 1.3 sec, and this must be considered as a serious discrepancy.

It seems very difficult to explain the above divergence from the systematics unless there are two 1014 keV transitions in the decay of Bi^{205} having relative intensities of about 2 ($M4$ transition) and 7. The energies of these transitions would be very nearly the same, since no line broadening was observed in the conversion-line measurements either in the double-focusing or in the permanent magnet spectrometer. It is not impossible that a repeat of the measurements with still better resolution could solve the problem. The K/L ratio measured (see section I.2.c) is not inconsistent with a mixture of two transitions, but better statistics are necessary for definite conclusions to be drawn.

As mentioned in Section I.2.c, the 1014 and 1552 keV transitions sum up to the energy of an excited state in Pb^{205} and it is therefore tempting to believe that the 1552 keV transition populates the isomeric state. However, in gamma-gamma coincidence studies on Bi^{205} [25] a strong coincidence effect has been observed between gamma rays of approximately 1 MeV and gamma rays of approximately 1.55 MeV. On the basis of the energy sums this effect has been interpreted as coincidences between the 1552 and 1014 keV gamma rays. Thus this result lends strong support to the suggestion made above that there exist two transitions of about 1014 keV in the decay of Bi^{205}. Conclusive information in this situation might be gained, besides from the conversion measurements suggested above, from prompt and delayed coincidence experiments.

3. *The 703.3 keV state*

In view of the $E3$ character of the 310.5 keV transition taking place between the 1013.8 keV 13/2+ state and the 703.3 keV state, the most probable spin and parity assignment of the latter state seems to be 7/2−. A 9/2− assignment may, however, not be completely excluded. It is interesting to find that the theoretical calculations of Pryce [19] and True [20] definitely indicate 7/2 − for this level. According to earlier experiments, however, the 9/2− assignment was considered preferable, mainly due to the multipolarity $E2$ of the 703.3 keV transition [3]. The K-conversion coefficient of this transition has recently been accurately measured to be 0.011 ± 0.001 [7], and since the theoretical values for the multipolarities $E2$ and $M1$ are 0.0105 and 0.036 [8], respectively, a possible admixture of $M1$ should be well below 10 %.

The difficulty involved in a 7/2 − assignment of the 703.3 keV state and the $E2$ character of the transition to the 5/2 − ground state is, however, probably over-estimated. According to the simple model, the transition takes place between $p_{1/2}\,(f_{5/2})^2$ (7/2) and $(p_{1/2})^2\,f_{5/2}$ (5/2) states. This involves one nucleon (hole) changing from $f_{5/2}$ to $p_{1/2}$, and this can be done only by an $E2$ transition (or, much less probably, by an $M3$), but not by an $M1$ transition. Any $M1$ character must be due to configurational mixing, and its absence speaks for a reasonable purity of the states [26].

Shortly after a brief report of the present work had been submitted to the Physical Review [27], the author became aware of the results of Alburger [28] from his recent study on this subject. Besides identifying a (26 ± 1) keV $M2$ transition, Alburger carried out coincidence experiments and found that the M- and N-internal conversion lines of the 26 keV transition are not in coincidence with electron-capture K X-rays, but that they are in coincidence with a principal gamma ray of 1 MeV and weak components of about 0.7 and 0.3 MeV. In view of the results of Vegors and Heath [5], showing that the gamma rays of 987.8 and 284.2 keV and a fraction of the 703.3 keV gamma rays are delayed with respect to electron-capture K X-rays, the coincidence results of Alburger indicate that the delayed radiation is associated with the 26 keV transition originating from an isomeric state in Pb^{205} at 1013.8 keV.

It is gratifying to find that the two investigations, carried out independently during about the same period of time, complement each other and lead to consistent conclusions. It is felt that the two pieces of work, together with the work of Vegors and Heath, give a reasonably complete solution of the problem of "the missing isomer in Pb^{205}".

APPENDIX

1. *Additional conversion-line measurements with isotope-separated sources of* Bi^{205} *and* Bi^{206}

In connection with the investigation of the isomeric transitions in Pb^{205} some other transitions were also studied in the double-focusing spectrometer using the electromagnetically isotope-separated sources of Bi^{205} and Bi^{206}. Some interesting results were obtained and will be detailed below. The energy and intensity data obtained with the Bi^{205} source are collected in Table 5.

a. *The 90.04 keV transition in* Pb^{205}

In a photographic film, exposed in a permanent magnet spectrometer, Schmorak *et al.* [3] observed three weak conversion lines having energies corresponding to the possible assignments L_{I} 90.0 or K 162.2, L_{II} 89.9 and L_{III} 90.1. (A possible L_{I} 162.2 line would be masked by K 234.3 of Bi^{206}.) The present results from the measurements of these lines in the double-focusing spectrometer strongly indicate that the lines are the L_{I}, L_{II} and L_{III} conversion lines of a 90.04 keV transition. As can be seen in

Table 5. Additional conversion lines studied with an electromagnetically separated source of Bi^{205}.

Adopted transition energy (keV)	Internal conversion lines measured	Relative conversion-line intensity ($I_{K\,703.3} = 100$)	Internal conversion relations[a]	Multi-polarity suggested
90.04 ± 0.04	L_I 90.06 L_{II} 90.04 L_{III} 90.02	15 ± 3 5.4 ± 1.5 7.4 ± 1.5	$L_I/L_{II}/L_{III} =$ $= (2.0 \pm 0.6)/(0.7 \pm 0.2)/1$	$E1$
115.15 ± 0.05	K 115.19 L_I 115.09 L_{II} 115.11	81 ± 8 17 ± 3 1.9 ± 1.0	$K/\Sigma L = 4.3 \pm 1.0$ $L_I/L_{II} = 9^{+10}_{-5}$ $L_{III}/L_I < 0.05$	$M1$
185.3 ± 0.1	K 185.2 L_I 185.3	40 ± 4 6.6 ± 2	$K/(L_I + L_{II}) = 6.0 \pm 2$	$M1$, $E1$
260.5[b]	K 260.5 L_I 260.5	160 ± 15 29 ± 3	$K/(L_I + L_{II}) = 5.5 \pm 0.5$	$M1$[c]
262.8 ± 0.1	K 262.8 L_I 262.8	46 ± 5 8.8 ± 1.3	$K/(L_I + L_{II}) = 5.2 \pm 1.0$ $L_{III}/(L_I + L_{II}) < 0.07$	$M1$
313.1 ± 0.3	K 313.1	4.9 ± 1.0	$K/(L_I + L_{II}) > 2$ $L_{III}/K < 0.05$	$M1$, $E1$

[a] Experimental values; the comparison with theoretical values is made in the text.
[b] The value was used in the energy calibration.
[c] Unambiguously suggested from K-conversion coefficient [7].

Table 5, the energy agreement is better than $5:10^4$. (The K-conversion line could not be measured, since its energy is just below the G.M. window cut-off energy of 2.3 keV.) From the experimental ratios $L_I/L_{II}/L_{III} = (2.0 \pm 0.6)/(0.7 \pm 0.2)/1$ all multipolarity assignments except $E1$ must be excluded for the 90.04 keV transition. The theoretical ratios for $E1$ are 2.2/1.0/1 [8]. (The only other multipolarity which might possibly be considered is $M2$, for which the calculated ratios are 3.7/0.42/1).

b. *The 115.15 keV transition in Pb^{205}*

This transition was earlier identified from its K, L and M conversion lines [3] but, due to insufficient information about its internal conversion ratios, no multipolarity could be assigned. In the present investigation the lines were measured with a resolution of about 0.35 % in the double-focusing spectrometer, and the internal conversion data obtained are included in Table 5. Comparing the experimental ratios $L_I/L_{II} = 9 \pm^{10}_{5}$ and $L_{III}/L_I < 0.05$ (no L_{III} component observed) with the ratios deduced from the theoretical L conversion coefficients, one finds that the only multipolarity which can be assigned to the 115.15 keV transition on this basis is $M1$ (cf. the theoretical values for $M1$ are: $L_I/L_{II} = 9.4$ and $L_{III}/L_I = 0.0085$ [8]). The experimental $K/\Sigma L$ ratio of 4.3 ± 1.0 is, however, lower than the theoretical value, which is 5.6 [8], but the disagreement is probably not so severe as to eliminate the possibility of an $M1$ assignment.

c. *The 185.3 keV transition in* Pb^{205}

The identification of this previously unreported transition is based on conversion lines found corresponding to the assignments K 185.2 and L_{I} 185.3. A possible L_{III} line would be hidden under the strong K 260.5 line. Taking into account also results obtained with a permanent magnet spectrometer, the value 185.3 keV is adopted for the transition energy. The measured conversion ratio $K/(L_{\mathrm{I}}+L_{\mathrm{II}}) = 6.0 \pm 2$ suggests an $M1$ or $E1$ assignment for this transition (cf. the theoretical values are: 5.7 for $M1$, 6.5 for $E1$ [8]).

d. *The 262.8 keV transition in* Pb^{205}

In the decay of Bi^{206}, a transition of 262.8 keV is known to take place [29]. Since in the earlier beta-spectrometric investigations of Bi^{205} [2, 3] sources containing both Bi^{205} and Bi^{206} have been used, the very strong conversion lines of the above 262.8 keV transition have always been present in the conversion-line spectra. The lines are situated close to those of the 260.5 keV transition in the decay of Bi^{205}, as can be seen on the photographic film in Fig. 3 of ref. [3]. However, in a private communication, Vegors states that he believes to have conclusively established that there are two Bi^{205} gamma rays in this region having energies of 260.5 and $(260.5 + 2 \pm \frac{1}{2})$ keV. The conversion lines of the latter gamma ray should thus have been completely masked by the above-mentioned Bi^{206} lines in the investigations of Bi^{205} referred to above.

The electromagnetically isotope-separated sources were considered well adapted to a closer study of this new transition in Pb^{205}, and, with the purpose to determine its energy, intensity and multipolarity, measurements were carried out in the double-focusing spectrometer with a relative half-width of about 0.35 %. The results obtained with the isotope-separated sources of Bi^{205} and Bi^{206} are shown in the upper and lower parts, respectively, of Fig. 7. A comparison between the two spectra gives a direct proof of the existence of the new transition. This follows immediately from the fact that, in the Bi^{206} run, the K 262.8 line intensity is found to be approximately one third of the L 184.1 line intensity (in agreement with ref. [29]), which means that the contribution of K 262.8 (Bi^{206}) is almost negligible in the Bi^{205} run. The energy determination shows (cf. Table 5) that the new transition has the same energy, 262.8 keV, as the transition in the Bi^{206} decay.

The presented case illustrates the uncertainty involved in measurements with mixed sources. The conversion lines, which in this case had been missed, are among the strongest in the decay of Bi^{205} (cf. Table 5 and ref. [3]). The circumstances are the more serious since the 262.8 keV transition seems to be a very important transition in Pb^{205}, namely the transition originating from the first excited state, as will be discussed below (see Appendix 2.a).

As shown in the inset of Fig. 7, also the L lines of the 260.5 and 262.8 keV transitions in Pb^{205} were measured. From an investigation by Stockendal and Hultberg [7], the 260.5 keV transition was proved to have mainly magnetic dipole character from the measured values of the K-conversion coefficient[1] and $K/(L_{\mathrm{I}}+L_{\mathrm{II}})$ ratio. The value of $K/(L_{\mathrm{I}}+L_{\mathrm{II}})$, as deduced from Fig. 7 for this $M1$ transition, is 5.5 ± 0.5, in agree-

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[1] The contribution of photoelectrons from the 262.8 keV gamma ray was obviously not taken into account in the determination of ε_K for the 260.5 keV transition. The correct value is therefore somewhat higher and in better agreement with the theoretical value for $M1$.

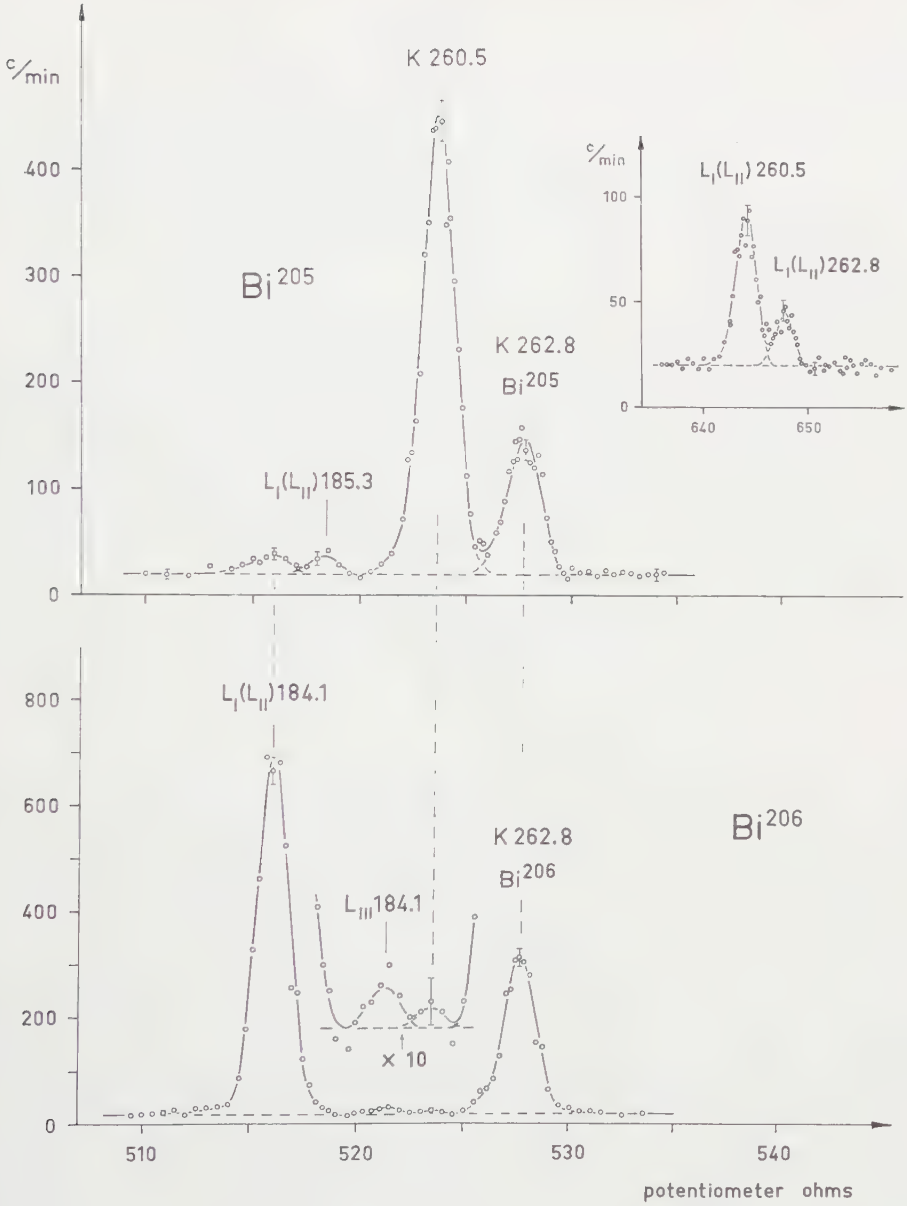

Fig. 7. Proof of the existence of 262.8 keV transitions in both Bi^{205} and Bi^{206} decays from measurements with electromagnetically isotope-separated sources. Both transitions have the same multipolarity, thus increasing the difficulties in interpretation when using a source containing both Bi^{205} and Bi^{206}. The conversion-line spectra were measured in a double-focusing spectrometer at 0.35 % resolution.

ment with the value of 5.8 ± 0.5 earlier obtained (cf. the theoretical value for $M1$ is 5.7 [8]). The $K/(L_I + L_{II})$ ratio found for the 262.8 keV transition is 5.2 ± 1.0, which indicates that also this transition is mainly of multipolarity $M1$, since for any other multipolarity the theoretical $K/(L_I + L_{II})$ ratio [8] lies outside the experimental limits of error. The $M1$ assignment is consistent also with the fact that no L_{III} component appears in the conversion-line spectrum, as is shown in Fig. 7 ($L_{III}/(L_I + L_{II}) < 0.07$; cf. the theoretical value is 0.007 for $M1$ [8]). It may be mentioned here that also the 262.8 keV transition in Pb^{206} has $M1$ character [29].

e. *The 313.1 keV transition in* Pb^{205}

In connection with the study of the isomeric 310.5 keV transition, a new line, stronger than K 310.5, was detected, as mentioned in Section I.2.b. The line is interpreted as the K-conversion line of a 313.1 keV transition since, if it were an L line of another transition, the corresponding K line would be missing. The line was undetected in earlier measurements because it was masked by the K 313.6 line of Bi^{206}. The L_I and L_{II} lines of the 313.1 keV transition are unresolved from L_{III} 310.5, but nevertheless, by combining the lower limit obtained for $K/(L_I + L_{II})$ with the fact that no L_{III} component is observed, one can exclude all multipolarity assignments except $E1$, $M1$ and $M2$ for this transition. This is the conclusion drawn if no presumption is made about the multipolarity of the 310.5 keV transition. However, taking the $E3$ assignment of this transition into account, $M2$ should be excluded for the 313.1 keV transition.

f. *Low-energy conversion lines in* Pb^{206}

The lower part of Fig. 2 shows the energy region below 30 keV of the electron spectrum measured with an isotope-separated sample of Bi^{206} in the double-focusing spectrometer at 0.35% resolution. It may be of interest to compare this spectrum with that studied by Alburger and Pryce in an intermediate-image spectrometer at 4% resolution [29]. In the latter spectrum seven electron lines were found in the above-mentioned energy region, having energies of 10.2, 12.3, 14.3, 19.2, 23.2, 26.0 and 28.8 keV. Only one of these lines could be definitely assigned, namely the one of 19.2 keV, which is the K-conversion line of a 107.2 keV gamma ray. The energy of this line, as measured in the present work, corresponds to the assignment K 107.14 (cf. Fig. 2). Regarding the three first lines above, it can now be definitely concluded that they are made up of L Auger lines, the most prominent of which are seen as peaks at 10.06, 12.20 and 14.33 keV in both the Bi^{205} and the Bi^{206} spectrum of Fig. 2. The fifth and sixth lines of Alburger and Pryce are not seen in the present work, but this is, at least in the case of the sixth line, probably due to lack of intensity. The possibility that they should be due to a small admixture of the M and N lines of the 26.22 keV transition in Pb^{205} should be excluded since they are reported to decay with the Bi^{206} half-life. Finally, the line of 28.8 keV is probably identical with the internal conversion line of 28.29 keV seen in the present work.

Judging from Fig. 2, there does not seem to be conclusive evidence for the existence of any new internal conversion lines having energies below 30 keV.

The intensities (number of electrons per 100 disintegrations) of the two conversion lines of 19.14 and 28.29 keV were found to be 0.41 and 0.10.

2. *On the decay of Bi^{205}*

Earlier investigations have shown that the decay of Bi^{205} is very complex. Thus, for instance, Schmorak *et al.* [3] observed about 40 gamma rays in this decay, 28 of which were included in a level scheme. Since then more research has been done, and it would therefore be useful to discuss some suggestions of changes and completions in the proposed level scheme. However, in order to draw definite conclusions about a level scheme of this degree of complexity, accurate knowledge about coincidences between transitions is indispensable. Although a good deal of coincidence information is already known from the work of Schmorak *et al.* [3], more coincidence experiments, particularly on electron-electron coincidences, are certainly called for, especially with regard to the new transitions found. Such experiments have been planned to be started at this institute in the near future. For the meantime, however, a partly revised level scheme is suggested here (see Fig. 8), as based on results available to date. The energy values given in ref. [3] have in most cases been retained. For information about electron-capture feeding, coincidence effects, etc., and further data on transition intensities, see refs. [3] and [7]. The levels theoretically calculated by Pryce [19] are also indicated in Fig. 8. Some brief comments on the level scheme are given below.

a. Information of great importance for the determination of the first excited state in Pb^{205} is obtained from the following experimental results:

1. Harvey, who measured triton groups from a (d,t) reaction on lead, suggests levels at 270, 840 and 1790 keV [30]. The 270 keV level was assigned $p_{3/2}$.

2. Dagget and Grove found gamma rays of energies 260, 570 and 865 keV in the α-decay of Po^{209} [31].

3. Asaro and Perlman, who also studied the α-decay of Po^{209} [32], found a gamma transition of (260 ± 2) keV. From conversion coefficient information, this transition was considered to be magnetic dipole.

When the level scheme suggested by Schmorak *et al.* [3] was constructed, the accuracy in the latter measurement had not been reported. For this reason, and since the experiments strongly indicated that neither the 260.5 nor the 284.2 keV transition could be associated with the first excited state, the latter was assumed to be situated at 282.3 keV. This was supported by energy relations and by the multipolarity $M1$ of the 282.3 keV transition. Furthermore, no other transitions were known with energies in the vicinity of 260–270 keV. However, when the accurate results of Asaro and Perlman became known, the above proposal for the first excited state was withdrawn [33]. Furthermore, Fritsch and Hollander suggested that the energy of the first excited state should be changed from 282.3 to 260.5 keV [2].

However, as pointed out by Fritsch and Hollander, it has not been proved that the (260 ± 2) keV transition found from Po^{209} α-decay is identical to the 260.5 keV transition found from Bi^{205} electron-capture decay. Furthermore, the coincidence experiments of Schmorak *et al.* [3] had definitely rejected the 260.5 keV transition as a ground-state transition. Lastly, if the 260.5 keV transition is placed lowest in the decay scheme, it does not appear to be populated from any higher level, since no energy relations including the 260.5 keV energy are found. This last-mentioned difficulty is serious, since it would also be hard to understand how the state con-

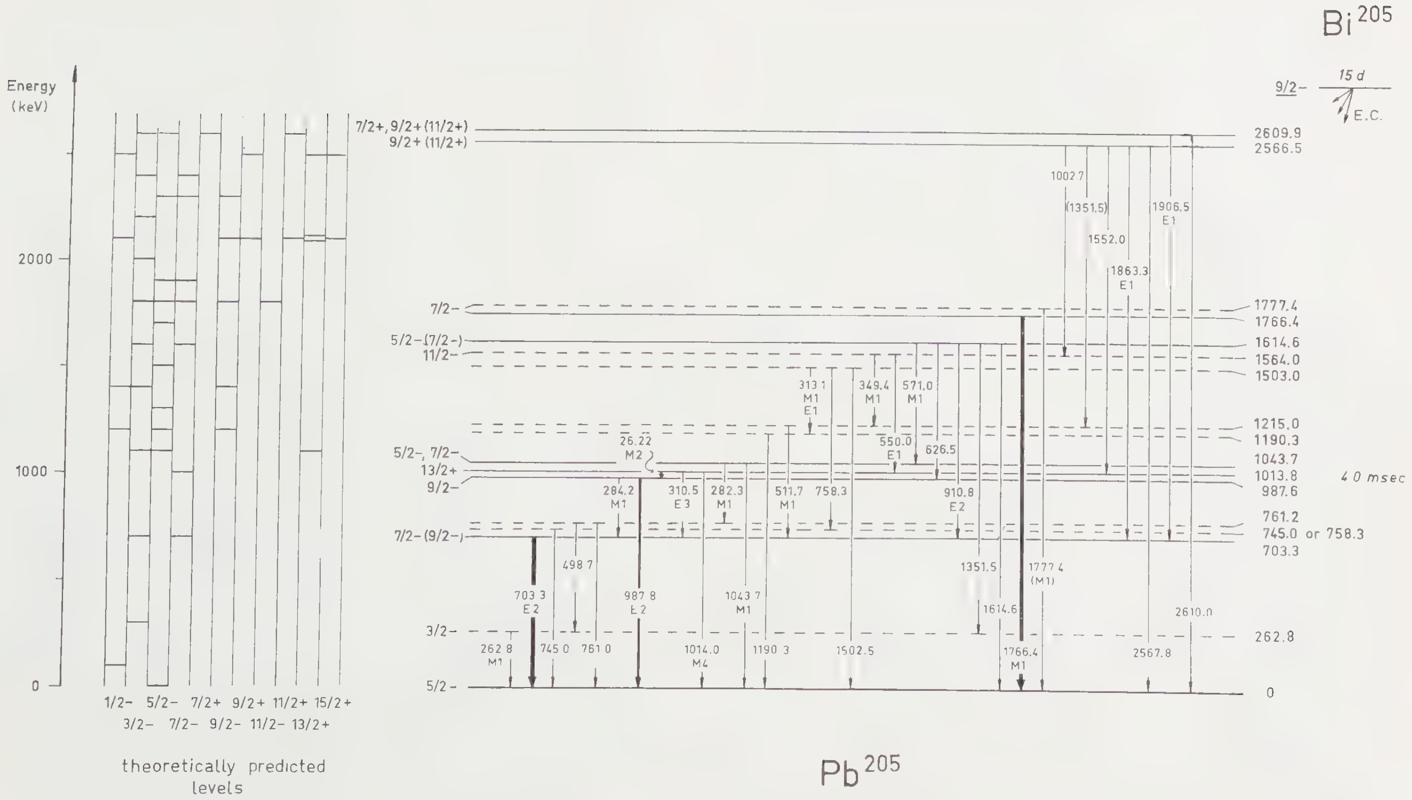

Fig. 8. Partially revised level scheme of Pb^{205}. For information about transition intensities, electron-capture feeding, coincidence effects etc., see also refs. [3] and [7]. The dotted lines indicate levels which are not quite definite. For the 1351.5 keV transition two alternative suggestions are given. The complexity of the level scheme shows the necessity of further electron-electron coincidence experiments, especially with high resolution. Levels theoretically predicted by Pryce [19] are shown to the left.

sidered (probably a 3/2 − state) can be entirely fed directly from the 9/2 − ground state of Bi^{205}.

The more recent experiments, however, have shown that there exists in the decay of Bi^{205} also an $M1$ transition of 262.8 keV (see Appendix 1.d). Since this energy value lies only slightly outside the upper limit given by Asaro and Perlman, and with regard to the difficulties outlined above, one might suspect that the first excited state is situated at 262.8 keV. A support to this hypothesis is given by the fact that the transition energies of 262.8 and 1351.5 keV, within the experimental error, sum up to the energy of a higher level:

$$262.8 + 1351.5 = 1614.3 \text{ keV}$$

$$\text{energy of level} = 1614.6 \text{ keV}.$$

Therefore, in the level scheme given in Fig. 8, the first excited state has tentatively been placed at 262.8 keV. It may be added that, on the assumption that the 1351.5 keV transition has a multipolarity $M1$ (which, however, has not been proved), then the total intensities of the 1351.5 and 262.8 keV transitions would be about the same (approximately 160 and 170 units, respectively, ($I_{K\,703.3} = 100$)). This would indicate that the main feeding to the 262.8 keV level goes via the 1351.5 keV transition. (The inclusion of a possible weak transition of 498.7 keV between the 761.2 and the 262.8 keV levels (see below), would be of no consequence in this respect.) Undoubtedly one of the most urgent experiments to be done on the decay of Bi^{205}, is to ascertain, by high-resolution electron-electron coincidence work, whether or not the 262.8 and 1351.5 keV transitions are in coincidence.[1] An alternative position of the 1351.5 keV transition is also shown in Fig. 8 (see also ref. [3]).

b. Since the 282.3 keV transition is no longer considered to be associated with the first excited state, one may be at liberty to place the cascade transitions of 282.3 and 761.0 keV in the reversed order, as was suggested by Fritsch and Hollander [2]. This has been done in Fig. 8 (with a mean value of 761.2 keV adopted for the energy of the intermediate level), mainly because this suggestion is in better agreement with the theoretical predictions, as shown in the figure. Furthermore, a minor support to this level sequence may be found in the fact that a very weak conversion line, which might be interpreted as the K line of the transition between the proposed levels of 761.2 and 262.8 keV, has been detected (cf. transition energy = 498.7 keV, level separation = 498.4 keV). The corresponding L-conversion line would be masked by the strong K 571.0 line. A difficulty with the inclusion of the 761.2 keV level is the coincidence effect observed between the 282.3 and 284.2 keV transitions [3]. However, the evidence for this effect is so small that it may be disregarded.

c. Concerning the two highest states, information was recently obtained from the experiments of Stockendal and Hultberg [7]. Both the high-energy transitions to the ground state were identified from internal conversion line measurements. Furthermore, the multipolarities of the 1863.3 and 1906.5 keV transitions to the 703.3 keV state were both found to be $E1$, thus indicating positive parity of the two highest states.

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[1] Quite recently, S. H. Vegors has privately communicated that coincidences have been observed between a gamma ray of approximately 260 keV and another of approximately 1350 keV.

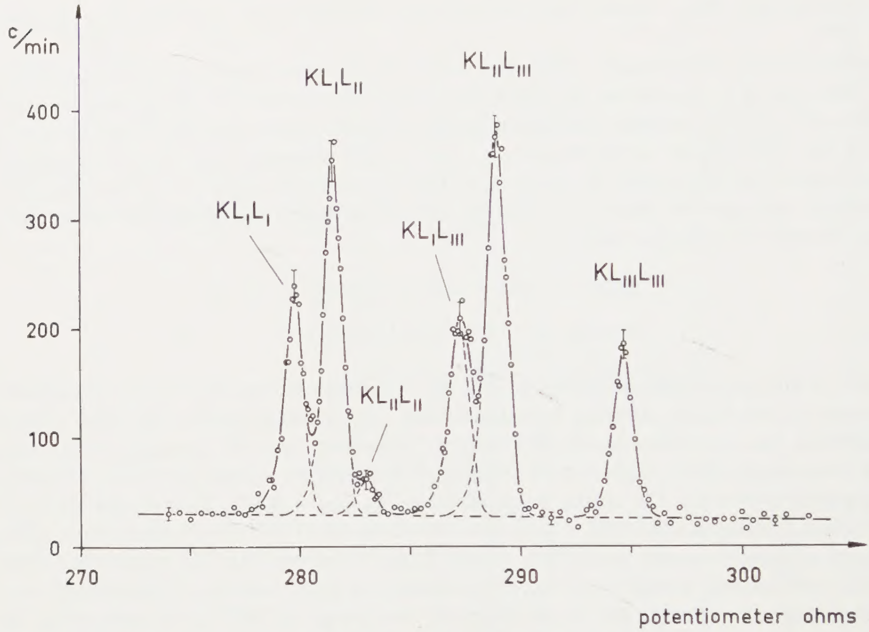

Fig. 9. The *KLL* Auger lines in Pb as measured in a double-focusing spectrometer at 0.35 % resolution. An electromagnetically isotope-separated source of Bi^{205} was used.

3. *Relative intensities of the KLL Auger lines in lead*

To the author's knowledge no experimental information has earlier been reported on the *KLL* Auger lines in lead. Fig. 9 shows these lines as measured in the present investigation with the double-focusing spectrometer at a resolution of about 0.35 %. An electromagnetically isotope-separated sample of Bi^{205} was used.

Recently, theoretical, relativistic calculations of the relative *KLL* Auger intensities in mercury have been made by Asaad [34]. It would therefore be of interest to compare these values with those experimentally found from Fig. 9. This is done in Table 6, and the agreement is seen to be fairly good. It may be mentioned that earlier theoretical predictions are not in agreement with experiments.

The table also includes the intensity values experimentally found for some other heavy elements. The values of Mihelich [35], Bergström and Hill [36], Ellis [37] and Mladjenović and Slätis [15] have been obtained from photographic films, whereas the values of Herrlander *et al.* [38], as well as the present results, were found from measurements in a double-focusing spectrometer. The agreement, especially between the latter two measurements, is remarkably good.

Since the *KLL* Auger lines were used for the energy calibration of the spectrometer (cf. Section I.2.a), it is not possible to make a direct comparison with theoretically calculated energy values. It should be pointed out, however, that the calibration constants for the spectrometer were obtained from an overdetermined system of equations, and the mutual consistency between all the energy data was excellent. This indicates that there is good agreement between the measured *KLL* Auger

Table 6. Relative intensities of KLL Auger lines.

Line assignment	Experimental values						Theoretical values
	Mihelich	Bergström and Hill	Ellis	Mladjenović and Slätis	Herrlander *et al.*	This work	Asaad
KL_IL_I	1	1	1	1	1	1	1
KL_IL_{II}	1.7	1.2	1.8	1.8	1.68 ± 0.21	1.62 ± 0.13	1.44
$KL_{II}L_{II}$	~ 0.3	~ 0.2	< 0.2	< 0.2	0.14 ± 0.07	0.15 ± 0.04	0.09
KL_IL_{III}	1.2	0.7	1.3	1.1	0.85 ± 0.13	0.87 ± 0.10	0.82
$KL_{II}L_{III}$	1.4	1.4	2.3	1.6	1.84 ± 0.24	1.80 ± 0.15	1.46
$KL_{III}L_{III}$	0.8	0.6	1.3	0.8	0.76 ± 0.11	0.75 ± 0.08	0.66
Z	79	80	83	83	80	82	80

energies and those calculated by use of ΔZ (cf. Section I.2.a). The only exception is the $KL_{II}L_{II}$ line, the measured value of which is considerably lower (0.2 %) than the calculated value.

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